开展近海生态系统长期观测引领海洋生态系统健康研究

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摘要　中国科学院胶州湾海洋生态系统定位研究站基于长期观测与系统研究，揭示了中国近海关键种——中华哲水蚤的度夏机制；在国际上，率先提出浮游动物功能群概念；阐明了全球变化影响下胶州湾生态系统的长期演变过程与机制；揭示了中国近海水母灾害暴发的关键过程、机理及生态环境效应；揭示了黄海绿潮成因，提出了黄海绿潮规模的预测思路和方法，形成系统化的防控应对策略；揭示了我国近海海水与关键海洋生物体内微塑料特征；研发了近海生态系统健康与承载力评估系统。相关研究在国内外产生了重要影响，为我国近海生态系统健康、生态环境保护、生物资源可持续发展提供了坚实的理论基础和科技支撑。

关键词　海洋生态系统，长期定位观测研究，海洋生态灾害，生态风险，健康评估

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近海海域具有重要的服务功能和价值。我国拥有约300万平方公里海域，大陆海岸线长达18 000多公里，是名副其实的海洋大国。海洋中丰富的天然资源和巨大的生态系统服务价值是保障我国社会经济可持续发展的重要基础，其重要性受到国家和社会的高度重视。

然而，我国近海面临多重胁迫，健康状况不容乐观。随着人们对海洋资源的开发和利用，我国近海陆续出现了一系列生态和环境问题，严重威胁和影响我国沿海经济的可持续发展。近年来，我国近岸海域富营养化问题日趋严重，局部海域污染问题突出，底层水体缺氧现象不断加剧；与此同时，有害藻华、浒苔、水母等不同类型的生态灾害在我国近海多次暴发，危害严重，近海生态系统呈现动荡状态；海洋垃圾、微塑料污染等新型生态风险层出不穷；多数传统优质鱼类资源量大幅度下降，难以形成渔汛[1]。我国近海生态环境的演变与生态系统功能退化问题已经成为制约沿海地区发展的重要因素，受到了国家和社会的高度关注。

开展近海生态系统的长期观测与系统研究，探究近海生态系统健康发展的理论、技术、方法、示范是服务于国家战略的重要举措。中国科学院胶州湾海洋

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生态系统定位研究站（以下简称“胶州湾站”）作为我国温带海域集监测、研究、示范于一体的综合性生态站，构建了完善的近海生态系统监测与研究平台，对胶州湾及邻近海域生态系统进行了长期观测，对海湾与近海生态系统长期变化、系统演变、驱动机理、发展趋势和应对措施开展了系统研究，揭示了维持海湾生态系统健康发展的关键过程，并提出相应的解决途径与系统方案，为我国近海生态系统的健康、可持续发展提供了重要的理论与技术支撑。

1 揭示中华哲水蚤度夏机制，率先提出浮游动物功能群概念

浮游动物是海洋生态系统动力学研究中的一个关键瓶颈问题，中华哲水蚤是我国近海浮游动物关键种。胶州湾站通过长期观测与研究，确定了中华哲水蚤的度夏场所为黄海中部冷水团，发现了中华哲水蚤度夏种群具备休眠特征，揭示了其完整的被动度夏过程（图 1）。该研究极大提升了我国浮游动物相关研究的国际地位，并以此为纽带将整个中国近海的浮游动物联系起来，证实了中国近海的中华哲水蚤为同一个种群的判断。对中华哲水蚤度夏的研究为其他海洋过程研究提供了重要支撑，使得中华哲水蚤主导的生态系统动力学数值模拟成为可能[2-5]。相关研究获得山东省自然科学奖二等奖。

胶州湾站在国际上率先系统提出了海洋浮游动物功能群的概念和划分方法（图 2）。对海洋渔业资源至关重要的浮游甲壳类动物功能群，由于其粒径大小是与鱼类之间摄食关系中的最主要的限制因子，因此胶州湾站根据粒径大小将浮游甲壳类动物功能群再次划分为大（粒径 >5 mm）、中（粒径为 2—5 mm）、小（粒径 <2 mm）3 个亚群。大、中和小型亚群的代表种类分别为磷虾类、大型桡足类和小型桡足类，又可分别称为大型甲壳类亚群、大型桡足类亚群和小型桡足类亚群。对于非饵料性浮游动物类群，将其划分为 3 个胶质类浮游动物功能群，分别为水母类功能群、海樽类功能群和箭虫类功能群。其中，水母类功能群和箭虫类功能群与高营养层次之间竞争摄食浮游动物及其生产力；同时，箭虫类也是高营养层次的一种食物来源。海樽类功能群，是一类被动的滤食性浮游动物功能群，与其他饵料浮游动物竞争摄食浮游植物，但其本身的物质和能量不能被有效传递到高营养层次。海洋浮游动物功能群概念的引入和应用为海洋生态系统健康评估、海洋渔业资源长期变动研究和海洋生态系统动力学过程模式的建立开辟了新的路径[6,7]。

2 阐明胶州湾生态系统的长期演变过程与机制

以胶州湾为代表性海域，基于 30 余年的综合观测

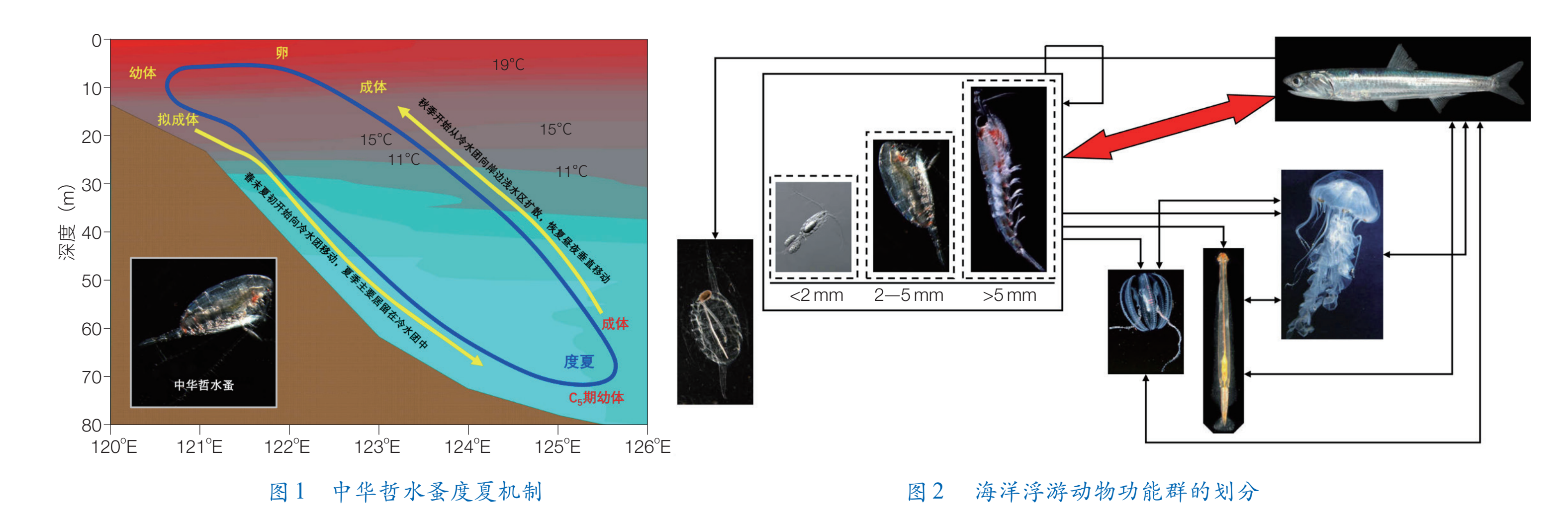


图 1　中华哲水蚤度夏机制

图 2　海洋浮游动物功能群的划分

和10余年的系统研究，发现近百年来胶州湾地区气温呈现波动上升趋势。其中，以冬季升温最为显著，可达0.080℃/a；胶州湾海水营养盐中氮过剩、硅缺乏，呈现出硅限制的可能性。

与此相对应，胶州湾暖水性浮游植物、甲藻等浮游植物类群的数量呈现升高趋势；浮游动物生物量同样呈现明显上升趋势，2000年之后浮游动物平均生物量为20世纪90年代的3.54倍，其中以水母类浮游动物的增加最为显著（图3）。而饵料性浮游动物，如大型桡足类的丰度平均值在2000年之后与20世纪90年代相比则降低了34.5%，整个生态系统呈现“营养盐比例失衡→甲藻类增多→浮游动物小型化、胶质化”的演变趋势[8-15]。

为辨析人类活动与自然变化对生态系统演变的影响，胶州湾站深入解析了胶州湾百年来的沉积讯息与环境变化的关系，发现人类活动对总有机碳、总氮、总磷、生源硅累积通量的贡献分别高达43.5%、37.2%、37.7%、30.0%，对重金属Cr、Mn、Ni、Cu、Zn、As、Cd、Pb的平均贡献分别达41.5%、23.5%、8.9%、48.0%、6.2%、9.8%、2.1%、21.6%，人类活动的影响主要始于20世纪80—90年代[16-19]。

基于胶州湾站的相关研究，出版了专著《海湾生态系统的理论与实践——以胶州湾为例》，为揭示近海生态系统的演变机制与制定可持续发展策略提供了系统的科学认识和指导。“胶州湾生态系统长期监测与系统研究”获得海洋科学技术奖一等奖。

3 揭示中国近海水母灾害暴发的关键过程、机理及生态环境效应

针对近年来胶州湾与中国近海频发的水母灾害开展了系统研究，查明了我国近海致灾水母的生物学特征、生长模式与生态适应策略，揭示了导致水母暴发的关键过程与调控机制、水母暴发对海洋环境和生态系统的影响途径与机理，提出了应对水母灾害的相关对策。

在水母暴发机理方面重点开展水母生活史无性繁殖阶段基础生物学和生态学研究，在水母生活史策略（图4）与环境变化及其关键调控因子研究方面取得突破。通过建立国内首个大型水母水族系统实验平台，率先完成对沙海蜇为主的致灾水母的人工繁殖和全生活史的室内培养，获得了沙海蜇、海月水母等我国近海致灾水母主要种类的生活史策略；发现了无性生活史是影响各暴发水母种群变动的重要生活史世代，环境条件（如温度、盐度、饵料等）的变化对其无性生活史策略的改变起着至关重要的作用；温度及其波动是调控致灾水母由无性生活史到有性生活史的

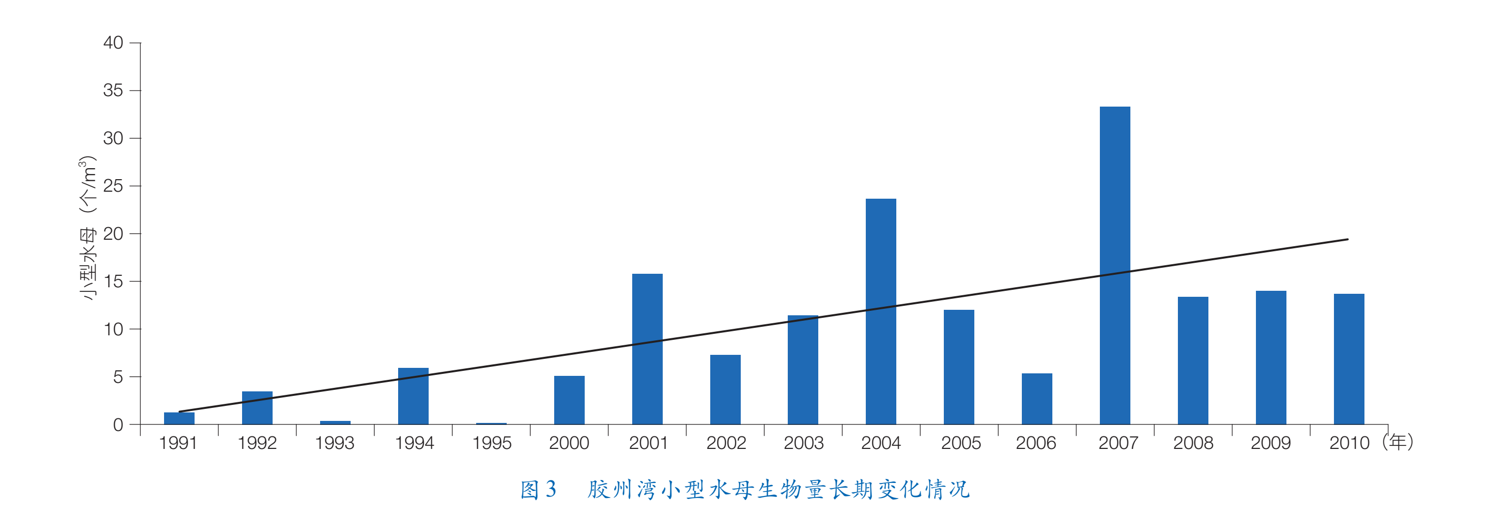


图3　胶州湾小型水母生物量长期变化情况

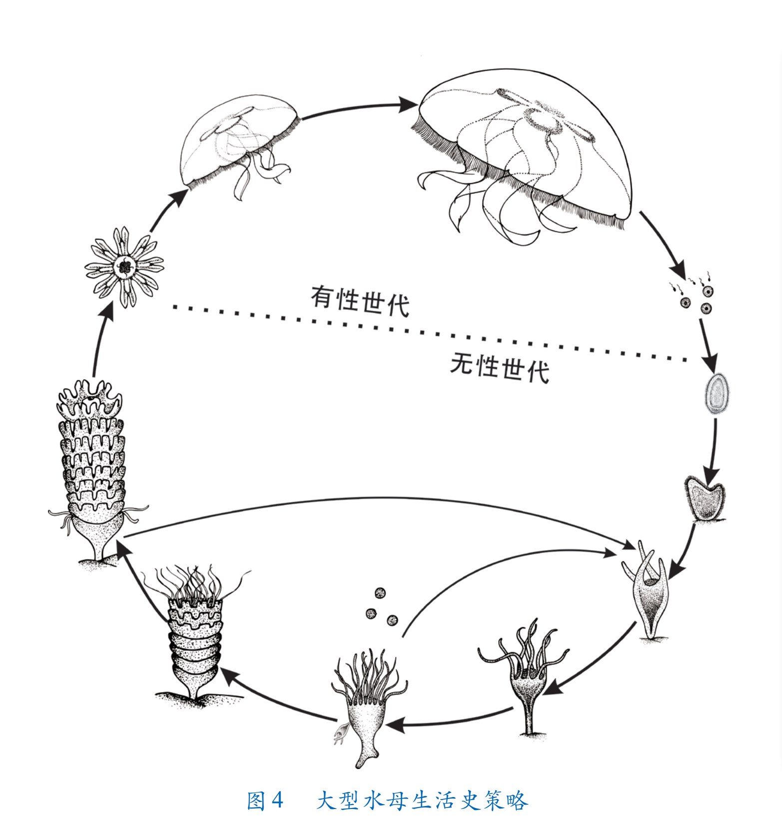


图 4　大型水母生活史策略



IN FOCUS NEWS

MARINE ECOLOGY

Coastal havoc boosts jellies

Five-year Chinese study suggests that human activity made gelatinous outbreaks worse.

BY JANE QIU IN QINGDAO

"It was a truly gelatinous world," says marine ecologist Sun Song, recalling a jellyfish outbreak last year in the Yellow Sea off China's eastern coast. "The slimy monsters were everywhere, their long tentacles fluttering ferociously in the rolling waves." Such blooms have repeatedly choked Chinese waters in the past decade, posing substantial threats to tourism, fisheries and coastal facilities such as chemical plants and nuclear power stations.

Jellyfish blooms have probably struck the world's seas periodically for hundreds of millions of years. But researchers suspect that human activity has made them worse, with knock-on effects on marine ecosystems and especially on fish, because jellyfish compete with fish for food and feed on their larvae. Now, one of the largest studies of jellyfish blooms so far — involving laboratory testing, ocean surveys and field experiments — has found direct evidence linking the proliferation of jellyfish to human disturbances along the coast, especially the disruption of sea-floor ecosystems.

The five-year, US$4.5-million initiative started work in 2010 led by Sun, who is director of the Chinese Academy of Sciences' Institute of Oceanology in the coastal city of Qingdao. Sun's team, involving eight institutions and more than 100 researchers, presented its latest results earlier this month at the World Conference on Marine Biodiversity, also in Qingdao. China's waters are not the only ones to have had jellyfish outbreaks in recent years, so the results "could help to tackle similar problems in other parts of the world" such as the Mediterranean or the Caspian Sea, says Mark Costello, a marine ecologist at the University of Auckland in New Zealand.

The survey shows that Chinese coasts are plagued primarily by three jellyfish species: *Aurelia aurita*, *Cyanea nozaki* and the most damaging one, the giant *Nemopilema nomurai*, which can grow to 2 metres in diameter and weigh as much as 200 kilograms.

Jellyfish are most recognizable in the short-lived 'medusa' stage of their life cycles, when they swim freely and reproduce sexually. But they also go through a stage in which they are bound to the sea floor as 'polyps'. These can live for years and reproduce asexually, budding new medusae. Most research so far has focused on the medusa stage, but "the key to jellyfish outbreaks may lie in the polyps", says Sun.

Polyps are notoriously difficult to find and collect: they are transparent and easy to break, and can be just micrometres long. "Numerous attempts by scuba diving, underwater robots and dredging up the sediments have led to nothing," Sun says. So the team turned to the jellyfish in the oceanology institute's aquarium. The researchers grew polyps on hard surfaces such as glass, plastic or stone in the laboratory and then lowered the slabs onto the seabed at half a dozen coastal locations, to see if specific environmental factors would spur a mini-outbreak.

As Sun reported at the conference, polyps of all three species tended to sprout medusae when sea-bottom temperatures were about 10–15 °C. The blooms were greatly enhanced by extreme temperature swings. Moreover, more medusae formed in waters that had fewer bottom dwellers, or 'benthos' — animals such as starfish, sea slugs, shrimp and fish — and greater environmental disturbance. Nutrient overloads from sewage and agricultural run-off, and construction of infrastructure such as ports and bridges, seemed to help the jellyfish to thrive.

The findings point to a link between the gelatinous scourges and coastal disturbances in China caused by overfishing, bottom trawling and oxygen depletion following algal blooms, as well as coastal development and increasingly frequent extreme-weather events, says Costello. Moreover, a decline in both the number and the diversity of benthos in the past 50 years may have also contributed, says Xu Kuidong, a marine ecologist at the Institute of Oceanology. Benthos that feed on polyps "are the key biological control of jellyfish populations", he says.

The ocean currents that skirt China's coast can affect benthos by changing temperatures and nutrient concentrations, so a broader approach will be necessary to unveil the true causes of jellyfish outbreaks, says Sun. In April, he and his colleagues launched a five-year, $165-million project to study ocean currents. By measuring the motion of currents at depths of up to 6,000 metres, and learning how ecosystems respond, the researchers hope to piece together how local and regional factors combine to cause blooms. "This might allow us to forecast — and even prevent — a forthcoming outbreak," says Sun.

And in May, an international collaboration launched the Jellyfish Database Initiative (JeDI), which will provide global, open-access data on jellyfish abundances and associated environmental factors. Such projects — as well as more-detailed studies of polyps — will attempt to improve understanding of outbreaks and the contribution of natural variations and human factors to changes in jelly populations around the world, says Cathy Lucas, a marine biologist at the University of Southampton, UK, who contributes to JeDI.

Sun says that increasing rates of jellyfish outbreaks in Chinese waters might be an indicator of worsening ecosystem health. Over the past 500 million years, the creatures have survived countless climatic and environmental upheavals — including all five known mass-extinction events, he points out. "When ecosystems deteriorate, they are likely to thrive when others fail." ■

SUN SONG

A polyp of *Nemopilema nomurai*, 1 millimetre long, will give rise to medusae more than 2 metres across.

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图 5　*Nature* 报导水母研究进展

扳机，调控能量在足囊（或出芽）与横裂生殖之间的分配。从整体上首次系统研究了影响我国 3 种致灾水母生活史的关键过程，揭示了控制其种群数量增长的关键控制因素，以及其关键发育阶段的生态适应策略，为揭示我国近海大型水母的暴发机理提供了重要的生物学基础[20-25]。

从生态系统水平上研究了我国近海水母暴发与生态系统变异之间的关系。首次系统阐明了黄海、东海沙海蜇自然种群的动态变化，并从生态系统的角度揭示了水母沙海蜇与生态系统变异之间的关系，预测水母持续暴发对我国近海生态系统演变的影响，提出应对水母灾害的相关对策，提升我国在海洋生态灾害过程与机制研究方面的总体水平、国际地位和影响力[26]。大型水母生活史策略和黄东海大型水母分布格局与生态系统变异之间的关系两项成果先后被评为海洋与湖沼十大科技进展，相关成果被 *Science* 和 *Nature* 跟踪报道（图 5）。国际著名海洋生态学家Mark Costello在评价时认为，“中国的水母暴发机理的研究结果为地中海、里海等其他海域的水母灾害问题提供了借鉴”。

胶州湾站在以上研究基础上，向科学技术部报送了《我国近海水母灾害情况报告与措施建议》，向中国科学院科学传播局报送了《沿海水母暴发对核电工业的威胁及应对措施建议》，并被采用。“黄东海大型致灾水母生活史及其灾害发生机制”研究获得海洋科学技术奖一等奖。

4 揭示黄海绿潮成因，形成系统化预测与防控应对策略

经过长达 10 年的研究，系统阐明了浒苔发源地、发生机制、防控机理，首次实现浒苔预测、预警、预报并得到验证，提出浒苔灾害防控系统解决方案，为海洋生态灾害综合防控和实施“健康海洋”战略起到科技支撑作用[27]。

从海洋生态系统角度，抓住关键过程开展综合研究，通过现场调查、卫星遥感和模拟实验等宏观和微

观研究手段，开展了系统的调查和研究工作（图6）。进一步确认了黄海绿潮起源于苏北浅滩海域，提出了对黄海绿潮总体规模的预测预警方法并成功预测了2017年度黄海海域绿潮规模显著下降的现象，形成了系统化的黄海绿潮防控策略，为2018年上海合作组织峰会的环境保障工作提供了重要的科技支撑。

提出了应用“绿潮综合指数”预测黄海海域绿潮总体规模的思路。“绿潮综合指数”包含了浅滩区浒苔微观繁殖体数量、筏架上定生浒苔的生物量，以及浅滩区漂浮绿藻的生物量等要素，有望提前30—40天预测黄海海域的绿潮规模，为黄海绿潮的预测、预警及综合防控提供科学支撑[28]。

根据对黄海绿潮成因和早期发展过程中关键点的分析，从消减绿藻微观繁殖体数量、控制微观繁殖体附着过程、回收筏架附着绿藻和绿潮早期漂浮绿藻的控制性打捞等角度开展探索研究。根据观测、实验和模拟结果制定整体防控措施，组织现场打捞实验（图7），提出绿潮防控“三道防线”的应对策略，为政府提供相关信息和系统解决方案。

5 揭示我国近海海水与关键海洋生物体内微塑料特征

海洋环境中的微塑料污染问题是当前国际和国家关注的热点问题，胶州湾站相关研究在该领域取得了系列进展。

（1）揭示了我国近海的表层水体微塑料分布特征。发现沿海大城市的近岸海域和黄东海中部海域微塑料分布密度较高（图8）。总体上东海表层水体中的微塑料的平均分布密度要高于黄海，与世界上其他区域比较，我国近海微塑料的分布密度处于中等水平[29,30]。

（2）系统揭示了黄海、东海浮游动物体内微塑料组成特征与分布格局。黄海、东海浮游动物体内普遍含有微塑料，通常端足类、枝角类体内微塑料含量较低，而箭虫、水母、磷虾、莹虾、海樽等体内微塑料含量较高。浮游动物体内以纤维状微塑料占主要部分，处于较高营养级的浮游动物体内微塑料相对更多，并揭示了浮游动物对微塑料的富集现象[31,32]。

（3）揭示了黄海19种鱼类体内微塑料的特征。与其他研究海域相比黄海鱼类体内微塑料处于中等水平；鱼类体内的微塑料主要为纤维；黄海北部与南部鱼类体内微塑料风险高于中部[33]。相关成果主要发表在*Environmental Pollution*、*Science of the Total Environment*等国际顶级期刊。

6 研发了近海生态系统健康与承载力评估系统

基于近海生态系统长期演变研究成果，针对国家

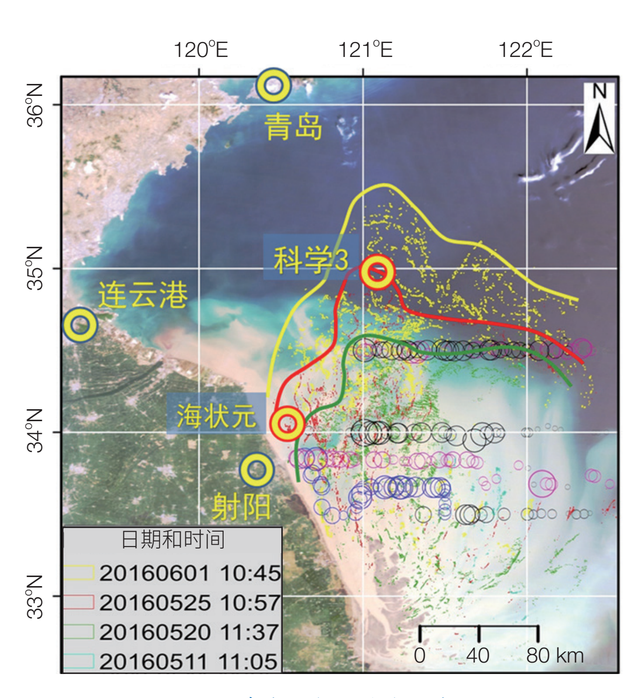


图6 黄海绿潮漂移路径追踪



图7 浒苔打捞现场

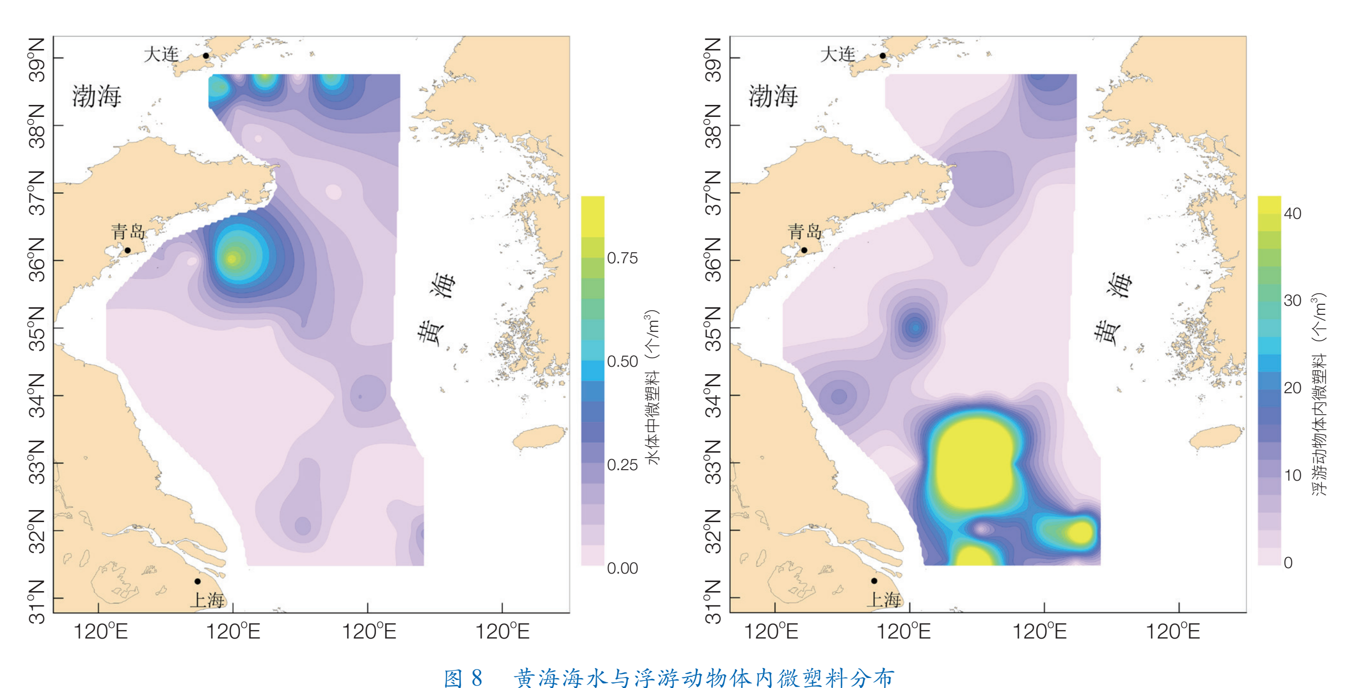


图 8　黄海海水与浮游动物体内微塑料分布

（a）表层海水中微塑料数量分布；（b）浮游动物体内微塑料数量分布

关心的我国近海生态系统健康与承载力问题，系统开展了近海生态系统健康与承载力评估，从近海渔业资源恢复和养殖模式改变两方面提出我国海洋渔业未来发展出路、对策与措施。

从与生态系统动态变化密切相关的相关要素现状及变化趋势，以及关键生态过程与生态系统变动之间关系出发，确立了我国近海生态系统健康评估框架；基于海域生态系统结构、服务功能及生态灾害/疾病等各项特征，完成了对各类数据资料的筛选、量化。利用机器学习技术，开展评估标准制定工作，对现有的标准进行改进，对尚未定义标准的进行标准的建立。以胶州湾为典型研究海域，完成卡片式健康评估模型框架的构建（图 9），科学评价胶州湾整体健康状况及其长期变化趋势。

研发的近海生态系统健康评估卡片分别在中国、澳大利亚近海典型海域进行应用，推动中澳健康海洋联合研究中心成立，中澳两国大使分别对胶州湾站主导的中澳健康海洋中心进行了访问。“中国近海典型海域生态系统健康评估”典型案例为联合国可持续发展目标（SDG）在 SDG14 指标监测中的方法模型、数据产品和决策支持方面作出了中国贡献。相关研究取得了良好的政治、经济和社会效益。

7 结语

长期以来，胶州湾站始终坚持长期监测、系统研究、示范服务的宗旨，面向国家海洋生态文明建设、“一带一路”建设等国家重大需求，面向海洋生态学领域的学科前沿，面向国民经济的主战场，取得了一系列创新性科研成果，为我国近海生态系统健康与可持续发展提供了重要的科技支撑。近 5 年来，以胶州湾站为研究平台，支撑了一系列重大科技项目，包括战略性先导科技专项、“973”计划、国家重点研发计划、国家自然科学基金重点项目、科学技术部对外合作重点项目等项目100 余项。获省部级奖项 9 项，发表研究论文 373 篇，申请和授权专利 31 项，出版专著 10 部，在国内外产生了重要影响。胶州湾站的长期

观测与系统研究在未来海洋生态系统健康与可持续发展中将发挥更大作用，为服务于国家战略提供更加重要的科技支撑。

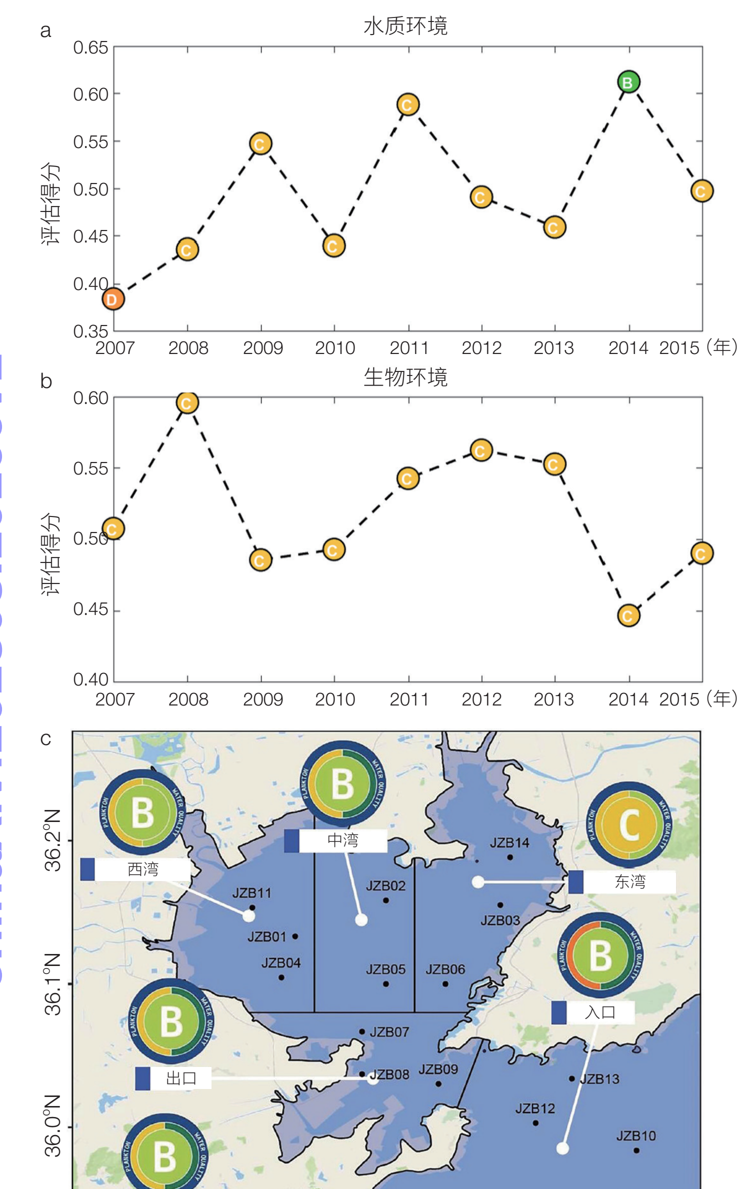


图 9　基于胶州湾生态系统长期观测研发的近海卡片式健康评估系统

（a）胶州湾 2007—2015 年生态系统健康评估水质环境项评估得分变化情况（得分区间为[0,1]：最低分为 0，满分为 1）；（b）胶州湾 2007—2015 年生态系统健康评估生物环境项评估得分变化情况（得分区间为[0,1]：最低分为 0，满分为 1）；（c）胶州湾生态系统试验性健康评估结果，评估得分由 0 至 1 均成 5 个等级：A（0.8—1）、B（0.6—0.8）、C（0.4—0.6）、D（0.2—0.4）、E（0—0.2），即 A 表示生态系统健康状况优秀、B 表示状况良好、C 表示状况尚可、D 和 E 则分别表示状况差和非常糟糕

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Conduct Long-term Observations of Coastal Ecosystems and Lead the Marine Ecosystem Health Research

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Abstract　Based on long-term observation and systematic research of the Jiaozhou Bay Marine Ecosystem Research Station, Chinese Academy of Sciences, the over-summering strategy of *Calanus sinicus* was revealed, and the concept of marine zooplankton functional group was proposed firstly. The long-term change and mechanism of Jiaozhou Bay ecosystem under the influence of global change were clarified. The key processes, mechanisms and ecological impacts of the jellyfish disaster were revealed. The cause, the prediction method, and the systematic prevention and control strategy were proposed for the green tides of the Yellow Sea. The microplastic characteristics in China coastal seawater and key marine organisms were revealed. The ecosystem health and carrying capacity assessment system of China coast has been established. All the above achievements provided a solid theoretical foundation and scientific support for the ecosystem health, environmental protection, and the sustainable development of the biological resources of the China coast.

Keywords　marine ecosystem, long-term observation, marine ecological disaster, ecological risk, health assessment

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